METHOD AND APPARATUS FOR ABERROSCOPE CALIBRATION AND DISCRETE COMPENSATION

TECHNICAL FIELD OF THE INVENTION

The present invention relates to optical measurement and correction systems and methods, and, more particularly, to corneal topography and ocular aberrations measurement and correction systems and methods.

BACKGROUND OF THE INVENTION

Wavefront measurement systems are known in the art for measuring and modeling ocular aberrations, such as those taught by the assignee of the present invention (e.g., U.S. Pat. No. 6,271,914, the disclosure of which is incorporated hereinto by reference). This system and method uses Zernike polynomials to reconstruct an aberrated wavefront reflected from an eye and to calculate a desired profile for directing laser sculpting of the corneal surface. An exemplary schematic for such a wavefront measurement device is given in FIGURE 2 in the '914 patent.

Although a number of aberroscope designs are known in the art, calibration systems and methods are inadequate, as stated by the Optical Society of America Taskforce on Vision Science and Its Applications (VSIA-2000 and VSIA-2001). Calibration of wavefront analyzers is now typically performed at manufacturing sites, and not in the field. Further, classical lenses have primarily been used to provide a known amount of defocus by moving the lens back and forth in the optical path. This method has the disadvantages of being

useful for limited aberration types (defocus, spherical aberration, and coma) and having a high level of uncertainty.

Holographic optical elements are known in the art that can function as lenses. Among their advantages are that they are lightweight and relatively inexpensive, can generate unique optical functions not possible with conventional optical elements, and can be fabricated in a wide range of materials.

Thus there is a need for a standard device that could be mass produced for calibrating and validating aberrometers.

BRIEF SUMMARY OF THE INVENTION

The embodiments of the present invention provide a device, system, and method for calibrating an aberroscope, such as, but not intended to be limited to, wavefront measurement devices for use in objective measurement of optical aberrations. The present invention also encompasses a method for making such a device and system.

An embodiment of the aberroscope calibration device of this invention comprises an optical element that is insertable into an optical path of a wavefront analyzer. The optical element is adapted to induce a predetermined aberration in a wavefront for presentation to the wavefront analyzer. Since the form of the aberration is known, the wavefront analyzer can be calibrated by comparing the predetermined aberration with an aberration calculated by the wavefront analyzer.

In specific embodiments, the optical element may comprise a lens optimized for a specific power and aberration; a computer-generated hologram, such as a diffractive optical element; or a spatial light modulator. The optical element may be transmissive or reflective.

A system for calibrating an aberroscope in accordance with this invention can comprise an optical element and a wavefront analyzer, the wavefront analyzer further comprising a wavefront detector. The wavefront detector is

positioned at a downstream end of an optical path into which the optical element is placed.

A method for calibrating an aberroscope according to the teachings of this invention can comprise the steps of passing a substantially unaberrated wavefront along an optical path leading to a wavefront analyzer. A predetermined aberration is induced in the unaberrated wavefront to form an aberrated wavefront. The aberrated wavefront is induced by an optical element positioned in the optical path upstream of the wavefront analyzer. The aberrated wavefront exiting the optical element is analyzed by the wavefront analyzer. The wavefront analyzer is calibrated using data generated by the wavefront analyzer from the aberrated wavefront.

A method of constructing a device for calibrating an aberroscope according to the teachings of this invention can comprise the steps of determining a desired aberration and creating an optical element adapted to induce the desired aberration. The created optical element is positioned upstream of a wavefront analyzer to induce the desired aberration when it is desired to calibrate the wavefront analyzer.

The features that characterize the present invention, both as to organization and method of operation, together with further objects and advantages thereof, will be better understood from the following description taken in conjunction with the accompanying FIGUREs. It is to be expressly understood that the FIGUREs are for the purpose of illustration and description

and are not intended as a definition of the limits of the invention. These and other objects attained, and advantages offered, by the present invention will become more fully apparent as the description that now follows is read in conjunction with the accompanying FIGUREs.

BRIEF DESCRIPTION OF THE SEVERAL VIEWS OF THE DRAWINGS

FIGURE 1 is a schematic illustration of an exemplary aberrometer optical path in accordance with the teachings of the present invention.

FIGURE 2 is a schematic illustration of an alternate embodiment of an aberrometer optical path.

FIGURE 3 illustrates exemplary range shifts capable of being induced by an embodiment of the device of the present invention.

FIGURES 4-7 are ray tracing graphs used in a paraxial approach to calculate the spot size at a lenslet array focal plane.

FIGURE 8 illustrates a compound lens useful for inducing a known aberration in accordance with the present invention.

DETAILED DESCRIPTION OF THE INVENTION

A description of the preferred embodiments of the present invention will now be presented with reference to FIGURES 1-8.

The method and system of the present invention comprise a plurality of embodiments for calibrating an aberrometer, for example, a wavefront analyzer, used to measure aberrations in an optical system. In a particular embodiment, the optical system comprises an eye, in which case the aberrometer is intended to measure optical aberrations preparatory to undertaking a corrective procedure, such as corneal ablation.

Embodiments of the system of the present invention comprise an optical element and a wavefront analyzer (aberrometer) for calibrating the wavefront analyzer. The wavefront analyzer may comprise, for example, a Hartmann-Shack wavefront sensor, although this is not intended as a limitation. In an exemplary embodiment illustrated in part in FIGURE 1, such a wavefront sensor comprises a lenslet array **11**, such as is known in the art, that samples a wavefront at regularly spaced points and transmits the sampled points onto a detector **12**.

In the case of a wavefront analyzer for use in measuring ocular optical aberrations, a wavefront reflected back from an eye contains data describing the eye's aberrations. As the measured aberrations are typically used to construct

a prescription for a corrective procedure, it is important that the wavefront analyzer is calibrated so that an accurate prescription may be derived from the collected data.

An overarching principle of the present invention is therefore to provide a device and a method for inducing predetermined aberrations in a known wavefront, typically an unaberrated wavefront, so that a comparison of aberrations actually measured and calculated by the wavefront analyzer can be made with those that are theoretically expected from the predetermined aberrations. Adjustments can then be determined and made to the calculational process of the wavefront analyzer to compensate for any deviations from the expected measured results.

The optical train **10** of FIGURE 1 includes an entrance pupil **13** through which is admitted a wavefront **14** for analysis. A first afocal relay system **15** comprises, for example, a pair of lenses comprising a first focusing, or converging, lens **16**, and a first collimating lens **17**. First collimating lens **17** is positioned downstream of a first focal point **18** of the first focusing lens **16**. The first afocal relay system **15** images the source of the incoming wavefront **14** onto intermediate pupil plane **19**.

Downstream of the intermediate pupil plane **19** is positioned a second afocal relay system **20**, formed, as in the first afocal relay system **15**, by a pair of lenses comprising second focusing lens **21** having second focal point **22**, and second collimating lens **23**. The second afocal relay system **20** images the

intermediate pupil plane **19** onto a lenslet array **11** plane. The lenslet array **11** samples the wavefront **14** in a number of wavelets, which impinge onto the detector **12** downstream of lenslet array **11**. Respective focal lengths $f_1 - f_5$ are shown below the optical train **10** of FIGURE 1.

An alternate architecture for an optical train **30** is illustrated in FIGURE 2, this architecture requiring fewer elements and a smaller footprint. The optical train **30** includes an entrance pupil **31**, and a first afocal relay system **100** comprising a pair of lenses. The lenses comprise a first focusing, or converging, lens **32**, and a first collimating lens **33**. First collimating lens **33** is positioned downstream of a first focal point **34** of the first focusing lens **32**. The first collimating lens **33** receives a wavefront **35** from the first converging lens **32** at a first face **36** and outputs a collimated wavefront **37** from a second face **38**.

The first afocal relay system **100** of FIGURE 2 images the entrance pupil **31** onto intermediate pupil plane **39**. A reflective optical element **40** is positioned at the intermediate pupil plane **39**. Between the lenses **32** and **33** is positioned a beamsplitter **41**, which may comprise a pellicle beamsplitter, through which the wavefront **35** exiting the first focusing lens **32** passes substantially unaltered.

The reflective optical element **40** serves to reflect the wavefront **37** exiting the first collimating lens **33** back through lens **33**, the path of the reflected wavefront **37'** now reversed, so that the first collimating lens **33** also serves as a second converging lens. The reflected wavefront **37'** is reflected by the

beamsplitter **41** toward a second collimating lens **42**, where reflected wavefront **37'** exits second collimating lens **42** as wavefront **43**. Wavefront **43** impinges upon a lenslet array **11**. Focal lengths $f_1 - f_5$ are shown in FIGURE 2 alongside their respective optical path segments.

An optical train such as optical trains **10** and **30** described above, or another such optical train as can be conceived by one of average skill in the art, can be used by the method and system of this invention to calibrate an aberroscope, such as, but not intended to be limited to, a Hartmann-Shack analyzer, including a lenslet array **11** and detector **12**. In accordance with the teachings of this invention, such an aberroscope calibration can be performed using the optical element having a known aberration in the optical train **10** and/or **30**. The optical element, an Aberroscope Calibration Device ("ACD"), induces a change of phase to a wavefront passing through or reflected by the optical element, and has a phase surface modeled to reproduce a desired ocular wavefront for transforming a parallel beam into the desired wavefront. Such an optical element may comprise, but is not intended to be limited to, a lens optimized for a specific power and aberration; a diffractive optical element (DOE) or computer-generated hologram (CGH); or a spatial light modulator (SLM), such as a liquid crystal SLM, a Micro-Electro-Mechanical Systems (MEMS) device, or a continuous membrane deformable mirror. The optical element may be transmissive or reflective.

The optical element (ACD) may be inserted into a wavefront measurement system at any of the following locations: the entrance pupil plane;

the intermediate pupil plane; or the lenslet array plane. In prior art systems, calibration of an Aberroscope is required to be performed at a manufacturing facility by introducing an aberrated wavefront at the entrance pupil plane. The embodiments of the present invention permit calibration to be performed at any time at an installed site without disturbing the Aberroscope installation. Further, the optical element of this invention may comprise a plurality of optical elements positionable one at a time in the optical train, such as, for example, by using a rotating turret holding the optical elements for serial insertion.

The ACD of the present invention can thus be used to perform calibration/validation of an instrument. For example, an ACD in a monochromatic collimated or diverging beam provides, with high accuracy, a wavefront containing a specific aberration (e.g., a Zernike spectrum). Although, theoretically, a phase function $\phi(x,y)$ can be introduced by either a refractive or a diffractive element and can be described in different mathematical forms, it may be determined that a particular CGH aberrator may be more easily designed using a Zernike polynomial description.

Embodiments of the ACD of this invention can also be used to provide discrete compensation, “shifting” the origin of measurement by a known value. As an example (see FIGURE 3), if a given wavefront measurement instrument has a range R_1 of measurement between -12D and +8D (the range of measurement is determined mainly by first-order aberrations, i.e., defocus), an ACD capable of inducing a defocus of -6D will shift the range R_1 to a new range R_2 of measurement up to -18D (i.e., range R_2 provides a range of measurement

from –18D to +2D). Similarly, an ACD capable of inducing a defocus of +6D will shift the range R_1 to a new range R_3, up to +14D (i.e., range R_3 provides a range of measurement from –6D to +14D).

Another embodiment of the method and system for Aberroscope calibration and discrete compensation of the present invention includes providing continuous compensation using adaptive optical elements, such as a liquid crystal SLM, a MEMS device, or a continuous membrane deformable mirror. Continuous wavefront compensation/correction is very useful in some applications related to detecting and measuring functional vision.

The accuracy of a wavefront aberration measurement in a Hartmann-Shack analyzer is in part determined by the spot size produced by a lenslet on the detector plane and by the separation between two adjacent spots. These factors depend upon a number of parameters, including, in the case of an eye wavefront measurement, the spot size produced by the retinal probe beam, δ_{retina}.

Pupil diameter and pupil magnification are also important. For example, with reference to the optical train **10** of FIGURE 1, the pupil magnification of the wavefront measurement instrument is given by:

$$M_{pupil} = (f_2/f_1) \times (f_4/f_3)$$

In the case of the optical train **30** of FIGURE 2, the pupil magnification becomes:

$$M_{Pupil} = f_4/f_1, \text{ because } f_2 = f_3$$

Also important are the lenslet array effective focal length, denoted as f_5 in FIGURES 1 and 2, the clear aperture of a lenslet, and the eye's aberration.

A paraxial approach to calculating the spot size at the lenslet array focal plane will be shown with reference to FIGURES 4-7. From the retina to the object space (FIGURE 4):

$$\frac{y_1}{\delta_{retina}} = \frac{1000}{D \times EFL_{emetrop}} \qquad \text{(Equation 1)}$$

The angle subtended by δ_{retina} is:

$$\varepsilon = \frac{\delta_{retina}}{EFL_{emetrop}} \qquad \text{(Equation 2)}$$

Newton's equations show that (FIGURE 5):

$$z \times z' = -f^2 \qquad \text{(Equation 3)}$$

and

$$\frac{y'}{y} = \frac{z'}{f} = \frac{f}{z} \qquad \text{(Equation 4)}$$

For an afocal relay system, the pupil magnification is (FIGURE 6):

$$M_{Pupil} = f_2/f_1 \qquad \text{(Equation 5)}$$

The angular magnification between pupils is:

$$\varepsilon'/\varepsilon = 1/\ M_{Pupil} \qquad \text{(Equation 6)}$$

Applying Newton's equations to the first and the second lenses, one obtains:

(Equation 7)

$$z_1 \times z_1' = -f_1^2;\quad z_2 \times z_2' = -f_2^2 \xrightarrow{z_1 = 100/D,\ z_1' = z_2} z_2' = \frac{100}{D} \times (M_{Pupil})^2$$

and

$$\frac{y_2'}{y_1} = \frac{y_2'}{y_2} \times \frac{y_1'}{y_1} = \frac{z_1'}{f_1} \times \frac{f_2}{z_2} \xrightarrow{z_1' \equiv z_2} \frac{y_2'}{y_1} = M_{pupil} \qquad \text{(Equation 8)}$$

The spot size in the lenslet focal plane may be calculated as (FIGURE 7):

$$\delta = 2\ (a+b) = EFL \times \varepsilon' + EFL \times \frac{d}{|z_2'|} \qquad \text{(Equation 9)}$$

where d is the lenslet size.

Equations 2, 6, and 7 then yield:

$$\delta = \delta_a + \delta_b \qquad \text{(Equation 10)}$$

where:

$$\delta_a = EFL \times \frac{\delta_{retina}}{EFL_{emetrop} \times M_{pupil}} \quad , \quad \text{(Equation 11)}$$

represents the retinal probe beam spot contribution to the spot size in the lenslet focal plane, and where:

$$\delta_b = EFL \times \frac{d \times |D|}{1000 \times M_{pupi}^{2}} \quad \text{Equation (12)}$$

is the refractive ocular error contribution.

If an ACD is introduced into the optical path, whether in an intermediate position or in front of the lenslet array, the eye aberration can be dramatically reduced, and by consequences the spot size on the detector plane, thereby improving spot separation at the detector.

Several example calculations of an ACD are presented below.

Example 1. Lenses inducing pure defocus:

Lens type	Power at 820 nm	Clear aperture	Radius of curvature	Conic constant	Thickness on axis	Glass
Plano-concave	-10D	12 mm	-51.04 mm	-0.5865	1.5 mm	BK7
Plano-convex	+10D	12 mm	51.04 mm	0.58215	3 mm	BK7

Example 2. Computer-generated holograms inducing spherical aberration:

ACD type	Clear aperture (mm)	$\Phi = A_2\rho^2 + A_4\rho^4$; phase eq. of the Binary Surface (rad)	Induced aberration in Terms of Zernike Polynomials (μm)
Negative spherical aberration	12	A_2=377 A_4=-377	C_4^0=-8.2
Positive spherical aberration	12	A_2=-377 A_4=377	C_4^0=+8.2

where ρ is the normalized radial aperture coordinate and the wavefront equation is $WF = C_4^0(6\rho^4 - 6\rho^2 - 1)$.

Example 3. Computer-generated hologram inducing pure coma:

For a clear aperture: 12 mm and λ=0.8 μm, the phase equation of the binary surface (in radians) is:

(Equation 13)

$$\Phi(X,Y) = \frac{A_4}{r_M^4} * \{[X^2 + (Y + y_0)^2]^2 - [X^2 + (Y - y_0)^2]^2 - 8\, y_0^3\, Y\}$$

where A_4=202; r_M=6 mm, and y_0=0.7 mm. The induced aberration in terms of Zernike polynomials is (in μm):

$$WF\,(X,Y) = \frac{3C_3^{-1}}{r_M^{\,2}}\,(X^2Y + Y^3) \quad , \qquad \text{(Equation 14)}$$

where $C_3^{-1} = -8.2$.

Using commercial optical-design software, the CGH can be modeled as a diffractive surface defined by a phase function. The phase function is specified by an equation that could be a radial or Cartesian polynomial, a Zernike polynomial, or a Sweatt model phase equation. Basically, the optical function $\Phi(x,y)$ is determined by ray tracing from the ocular wavefront to be generated to the focal point of the setup. As the CGH null has to work in the first diffraction order, a carrier frequency must be added to the phase function in such a way as to ensure the separation of the diffraction orders. The CGH will be appropriately titled or decentered with respect to the aberroscope axis.

Photolithography is probably the most commonly used technique for making CGHs. Binary optics provides three main advantages: the capability of producing complex diffractive structures; low production cost for two-phase-level elements; and the possibility of high diffraction efficiency with multilevel elements.

The phase function $\phi(x,y)$ reproduced by a diffractive binary element is wrapped to an interval between 0 and an integral multiple of 2π. The phase profile is given by:

$$\psi(x,y)=[\phi(x,y)+\phi_0] \bmod 2\pi \quad , \text{(Equation 15)}$$

where ϕ_0 is a constant phase offset. The two-level binary phase functions can be described in various modes, for instance, $\Psi_{binary}(x) = \pi$, when $½(x_k + X_{k+1}) \leq$

are the solutions of the equations $\phi(x,y) = 2k\pi$ and $\phi(x,y) = (2k-1)\pi$, respectively.

The surface-relief profile $h(x,y)$ for a CGH etched on a substrate with a refractive index n is given by:

$$h(x,y) = \frac{\lambda}{2\pi} \times \frac{\psi_{binar}(x,y)}{n-1} \qquad \text{(Equation 16)}$$

Typically, a CGH is designed to operate at a specific wavelength.

Example 4. Combination of two lenses producing a known aberration. FIGURE 8 illustrates a doublet **50** having the following specification: Entrance pupil diameter = 10 mm. The two elements are decentered ±2 mm with respect to the optical axis. The first element **51** is a plano-concave lens with a radius of curvature of 12.55 mm, a conic constant of 0.17, and a wedge (tilt) of 12°. The second element **52** is a plano-convex lens with a biconic convex surface having radii of curvature in two perpendicular planes of 15.23 mm and 15.05 mm. The wavefront aberration produced by this doublet expressed in terms of Zernike polynomials is:

$$WF(\rho,\theta) = C_3^{-1}(3\rho^3 - 2\rho)\sin\theta + C_4^{0}(6\rho^4 - 6\rho^2 + 1) \quad , \qquad \text{(Equation 17)}$$

wherein the first term represents coma and the second, spherical aberration; C_3^{-1}=7.94; C_4^{0} = -0.234; and ρ is the normalized radial aperture coordinate.

Example 5. Combination of two CGHs. In this example, a "doublet" of two CGHs provides a specified amount of coma *without* spherical aberration, a unique feature. For a clear aperture of 12 mm and λ=0.82 μm, the two CGHs that are decentered ±0.7 mm with respect to the optical axis have phase equations (in rad) given by:

$$\phi_1(r) = -0.164 \times r^4 \qquad \text{(Equation 18)}$$

$$\phi_2(r) = +0.164 \times r^4 \qquad \text{(Equation 19)}$$

where r is the radial coordinate (in mm). The induced aberration in terms of Zernike polynomials is (in μm):

$$WF(X,Y) = \frac{3C_3^{-1}}{r_M^{\,2}}(X^2Y+Y^3) \qquad \text{(Equation 20)}$$

where C_3^{-1} = -8.65, r_M = 6 mm; and X and Y are pupil coordinates (in mm).

A tolerance analysis related to the axial and transverse positioning of the ACD can show the sensitivity to alignment/positioning parameters. Such an analysis has been performed by the present inventor ("Ocular Aberrations Induced by Centration Errors in Waveguided Treatments," The Association for Research in Vision and Ophthalmology ("ARVO"), 2002).

Validation can be performed using an interferometric setup for any ACD standalone, as well as for an entire wavefront measurement instrument including

the ACD. In this case, a flat mirror can be placed in front of the lenslet array in order to test the system in double-pass mode.

It may be appreciated by one of average skill in the art that the present invention confers the benefit of improved wavefront accuracy. Further, compared with classical lenses that can generate limited types of ocular aberration, such as defocus error and spherical aberration, a computer-generated hologram can in principle reproduce any individual ocular aberration or a combination of different aberrations to generate a composite wavefront.

In the foregoing description, certain terms have been used for brevity, clarity, and understanding, but no unnecessary limitations are to be implied therefrom beyond the requirements of the prior art, because such words are used for description purposes herein and are intended to be broadly construed. Moreover, the embodiments of the apparatus illustrated and described herein are by way of example, and the scope of the invention is not limited to the exact details of construction.

Having now described the invention, the construction, the operation and use of preferred embodiments thereof, and the advantageous new and useful results obtained thereby, the new and useful constructions, and reasonable mechanical equivalents thereof now obvious to those of average skill in the art, are set forth in the appended claims.